

THE DESIGN OF A CARDIAC DEFIBRILLATOR

BY

R. J. SHEPHARD

From the War Department, Chemical Defence Experimental Establishment, Porton Down, Salisbury, Wilts.

Received April 14, 1960

The successful treatment of cardiac arrest or ventricular fibrillation is becoming increasingly recognized as a technical possibility, not only under the ideal conditions of an operating theatre but also in such situations as the hospital ward and the out-patient department. Already there have been reports of the complete resuscitation of patients apparently dead from coronary thrombosis (Beck *et al.*, 1956; Walton, 1960), and it seems likely that before many years have passed equipment for cardiac massage and electrical defibrillation will be a standard provision on any resuscitation trolley. However, the type of apparatus that should be used in such a situation is still a matter of dispute.

Several types of electrical defibrillator, ranging from a simple fuse-box system (Lucas, 1959) to complex machines with indication of current and stimulus duration (Perry and Trotman, 1958), are available commercially, but the safety of patient and surgeon is still a keen source of controversy (Wyatt, 1959; Kelly, 1959). Although simple defibrillating devices have sometimes been used with success in clinical practice, the circumstances have been such that it is difficult to be certain that on other occasions the patient has not been affected adversely by the defibrillator. Such uncertainties do not seem justified in an apparatus intended to preserve life, and accordingly a careful investigation has been made of the theoretical and practical dangers underlying the several systems of defibrillation. Evidence is presented that existing devices can supply an unnecessarily large current for a dangerously long time, and in the light of this experience a defibrillator with controlled current and stimulus duration has been designed and tested in experimental animals.

METHODS

Model I (Guy's Hospital Type).* This was developed by Sir Russel Brock and his associates in the Thoracic Surgical Unit, Guy's Hospital. A voltage selector and transformer permits 50, 100, 150, 200, or 250 volts to be applied to the electrodes. The stimulus duration is controlled by a simple manual push-button switch (Fig. 1A).

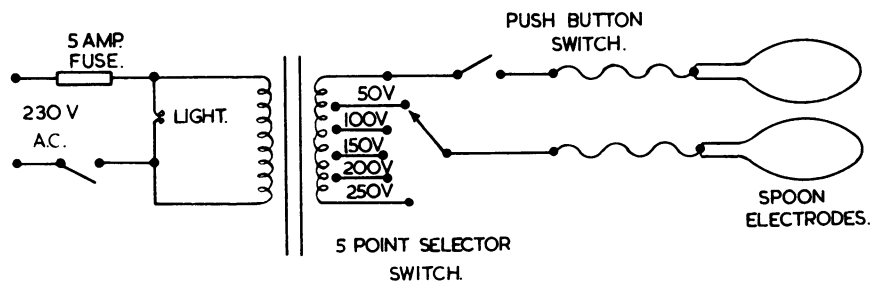


FIG. 1A.—Type I. Push-button controlled defibrillator (schematic diagram).

* Model I is available commercially from Rich and Bundy, Ltd., Ponders End, Middlesex. Model II is available from Howlett and Sons, Windsor. Model III is available from Electronic Machine Co. Ltd.

Model II (University College Type).* This was developed by Dr. Lucas, of the Anæsthetic Department, University College Hospital, as a simple form of emergency equipment. The mains voltage is applied directly to the electrodes, and stimulus duration is limited by a Belling-Lee type O glass cartridge fuse of 1 ampere rating (Fig. 1B).

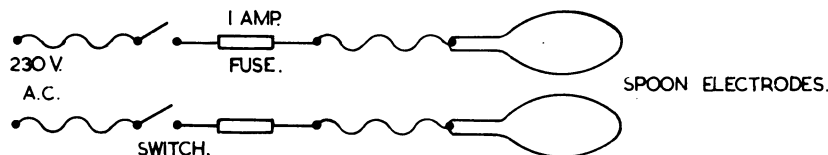


FIG. 1B.—Type II. Fuse controlled defibrillator (schematic diagram).

Model III (Westminster Hospital Type).* This was developed by the Physics Department, Westminster Hospital. The current passing to the electrodes is adjusted by a series rheostat, and the average r.m.s. current during the pulse is subsequently displayed. Stimulus duration may be controlled by either a hand switch or an RC circuit.

Porton Defibrillator. In view of theoretical shortcomings in Models I, II, and III, which are here demonstrated experimentally, a defibrillator was designed in which provision was made for rapid selection of maximum current and stimulus duration (Fig. 1C and D). This apparatus has been

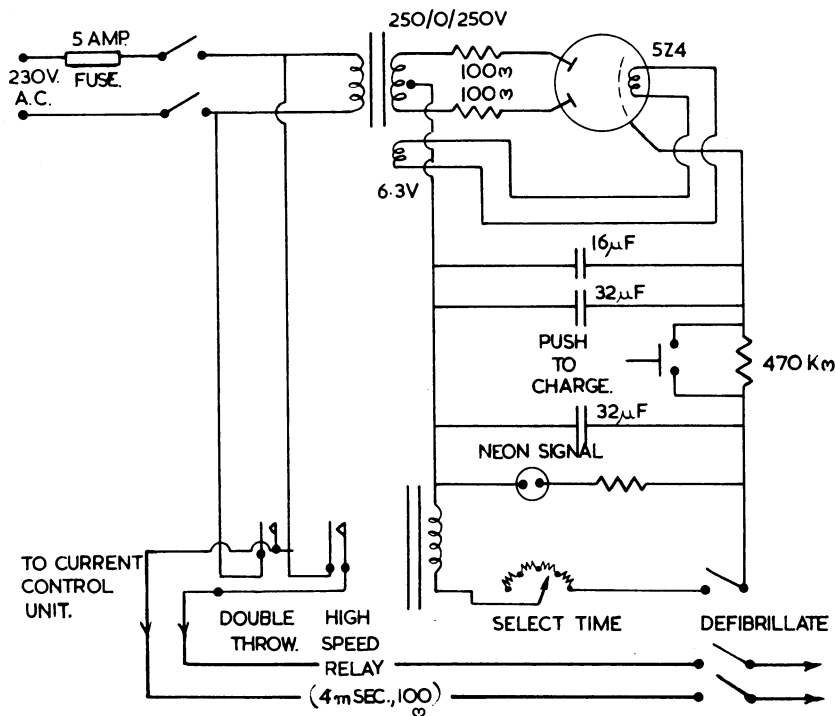


FIG. 1C.—Timing unit for Porton defibrillator (schematic diagram).

called the Porton defibrillator. The current is limited by selecting one of five banks of high wattage porcelain resistors (Birch), arranged in series with the electrodes. Appropriate resistance

* See note p. 1.

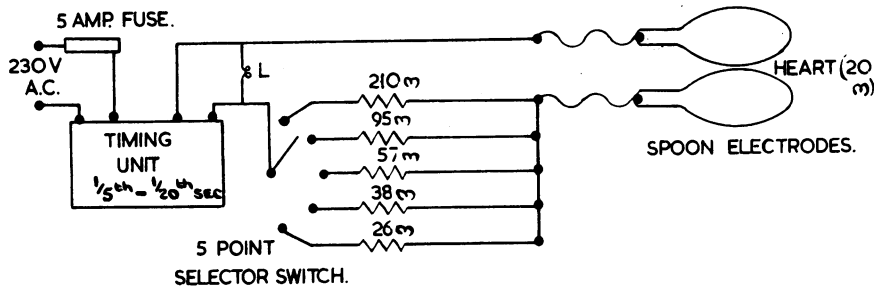


FIG. 1D.—Complete assembly of Porton controlled current electronically timed defibrillator (schematic diagram).

values have been calculated on the assumption of a minimum cardiac resistance of 20 ohms. A small increase in cardiac resistance will further limit the applied current and there will be a compensatory increase of applied voltage, but neither current nor voltage can reach a dangerous level. Stimulus duration is controlled to within 2 milliseconds by a simple flip-flop RC circuit, the operator pre-selecting a value in the range 0.05–0.20 sec. according to heart size. As an additional safeguard, the circuit is activated by a spring-loaded switch, and the operator releases this, disconnecting both electrodes, when a neon signal indicates completion of the shock.

Animal Preparations. The various types of defibrillator were tested on tracheotomized rabbits under pentobarbitone sodium anaesthesia (2 ml./kg. of solution 45 mg./ml. in 10% alcohol). The heart rhythm was monitored throughout by electrocardiogram (lead I). Artificial respiration was arranged and the heart exposed by a longitudinal incision through the left chest wall, lateral to the internal mammary artery. The pericardium was incised, and ventricular fibrillation induced by applying 6.3 volts 50 cycle alternating current to areas of ventricular muscle. As many as ten fifteen-second applications of the stimulating electrodes were often necessary to cause fibrillation that persisted after removal of the stimulus. When fibrillation had been maintained for one minute without stimulation, it was considered “established”, and the defibrillator used. The electrode size used was of a value appropriate for the rabbit heart. If necessary, massage was also applied, and when a normal rhythm was restored, the chest wall was roughly sutured. The operation was considered successful if an hour later the cardiogram was still normal and the animal was capable of spontaneous respiration. In a number of experiments, the resistance of the heart and electrodes was measured by an appropriate bridge circuit. In other experiments, an 0.01 ohm resistor was arranged in series with the electrodes, and the potential across this resistor was used to indicate the current passing through the heart during defibrillation. At the end of each experiment, the animal was killed by an overdose of sodium pentobarbitone, and the heart examined macroscopically and microscopically for burns and other signs of injury. In order to test the larger electrodes needed for human defibrillation, similar experiments were carried out on an anesthetized pig.

RESULTS

Safety. There is considerable danger to both subject and operator if the “live” pole of the electrode remains connected to the mains unknown to the operator. As has been pointed out (Wyatt, 1959; Kelly, 1959), this can occur with Model II if the neutral fuse blows prior to the live fuse. The suggested solution (Wyatt, 1959; Kelly, 1959) of momentary depression of the switch in effect converts Model II to Model I, operating at 230 volts. The alternative “safeguard” of removing the neutral fuse is also hazardous, as it is quite possible for the live and neutral leads of a mains socket to be transposed.

Model I and Model III can also be hazardous through failure of the push-switch to release or failure of the RC circuit.* The presence of a transformer limits the danger to some extent, but a

* There have been several instances where the push-button switch has failed in the operating theatre (Lucas: personal communication).

dangerously large current may be passed before it is realized that the coils are overheating. The only satisfactory safeguard would seem to be the incorporation of a second timing system, operating if the normal timing mechanism fails to limit stimulus duration. In the Porton defibrillator, this second line of defence is provided by the spring-loaded switch and neon indicator.

Strength of Applied Current. In models I and II, the strength of the current applied to the heart depends simply on the supply voltage (up to 250 v. a/c in Model I, and 230 v. a/c in Model II), and the electrical resistance across the electrodes. Resistance measurements by the a/c bridge have shown values of 10–12 ohms in the rabbit heart, and 17–22 ohms in the pig, varying slightly with different applications of the electrodes. Direct measurements of current strength during defibrillation of the rabbit heart with type I apparatus (Fig. 2) have shown values as high as 8 amperes during a 100 volt shock.

The probable current strength with use of the defibrillator in man can be calculated from the pig data. In the pig heart, with average cross-section of 35 cm.² and electrode separation of 4.5 cm.,

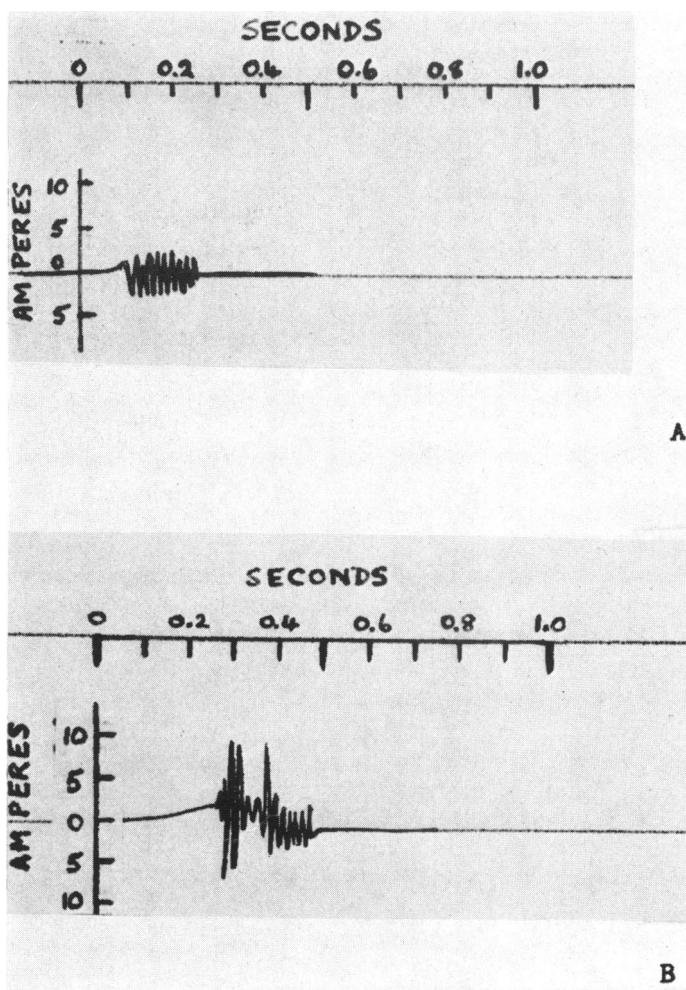


FIG. 2.—Current passing through rabbit heart using Type I defibrillation apparatus. (A) 50 volts stimulus; (B) 100 volts stimulus.

the calculated "specific resistance" is 143–186 ohm/cm., corresponding closely with the specific resistance of the blood (Rajewsky and Schwan, 1944). Assuming a similar specific resistance in man, and taking average cardiac dimensions (Johnston and Whillis, 1945), the resistance across the electrodes will be 15–20 ohms. With an applied potential of 250 volts, the instantaneous current could thus reach the alarming value of 16–17 amperes, with a power consumption of over four kilowatts. Although a transformer may have a much lower power rating, it can deliver currents of this order for a brief period, as can a fuse with nominal one ampere rating.

With commercial Model III, the current can be varied by means of a series rheostat, although the strength of current applied is not known until after the shock has been delivered. With the Porton defibrillator, the maximum applied current is known, and is largely independent of the resistance across the electrodes.

Stimulus Duration. In Model I and some forms of Model III, stimulus duration is controlled by a manually operated spring-loaded switch. A further, human, variable is thereby introduced. To test the possible range of variation a number of laboratory personnel were asked to deliver ten "short shocks" with a Model I defibrillator. Results are summarized in Table I. Initial observa-

TABLE I
STIMULUS DURATION WITH PUSH-BUTTON SWITCH OPERATED BY 11 LABORATORY PERSONNEL

| Operator | Quiet laboratory | | Stress situation | |
|------------|----------------------|-------------|----------------------|--------------|
| | Mean time \pm S.D. | Range | Mean time \pm S.D. | Range |
| | m.sec. | m.sec. | m.sec. | m.sec. |
| D.B. | 73.5 \pm 55.2 | 43.3–116.7 | 110.5 \pm 12.5 | 93.3–146.6 |
| F.B. | 121.2 \pm 34.0 | 60.0–183.2 | 110.5 \pm 32.5 | 53.3–163.3 |
| R.M. | 107.1 \pm 27.9 | 53.3–170.0 | 99.9 \pm 28.9 | 31.7–135.0 |
| R.S. | 125.0 \pm 34.2 | 58.3–178.3 | 144.0 \pm 28.8 | 136.7–186.6 |
| R.T. | 147.8 \pm 24.2 | 116.7–200.0 | 180.7 \pm 50.7 | 36.7–253.3 |
| D.P. | 84.2 \pm 10.5 | 70.5–105.0 | 122.5 \pm 19.9 | 96.7–175.0 |
| G.S. | 158.7 \pm 59.2 | 53.3–236.4 | 138.7 \pm 53.6 | 50.0–220.0 |
| B.A. | 121.8 \pm 24.2 | 90.0–196.6 | 153.4 \pm 26.2 | 71.7–375.0 |
| J.S. | 169.2 \pm 19.8 | 136.6–204.8 | 142.4 \pm 25.0 | 108.3–203.6 |
| S.T. | 199.0 \pm 74.2 | 61.7–304.6 | 220.7 \pm 105.3 | 75.0–535.0 |
| J.E. | 197.6 \pm 116.6 | 33.3–437.0 | 514.5 \pm 230.0 | 150.0–1028.0 |

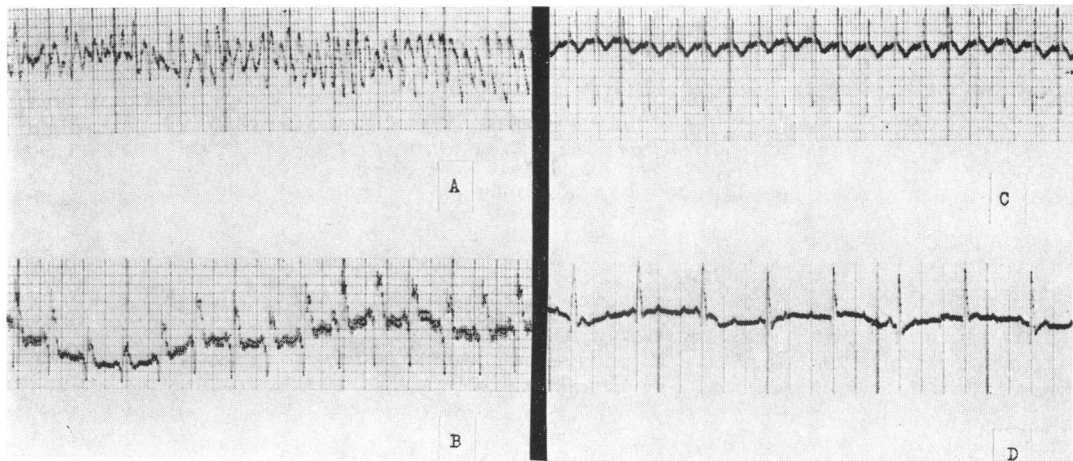


FIG. 3.—Defibrillation with Type I apparatus (rabbit). (A) Established ventricular fibrillation; (B) Immediately following 50 volt defibrillating shock for 0.2 sec. (sinus rhythm with broadened QRS complex and elevated RS-T segment.); (C) Same animal as (A) and (B) breathing spontaneously 30 min. later (normal sinus rhythm.); (D) Immediately following 100-volt defibrillating shock for 0.2 sec. (atrio-ventricular block).

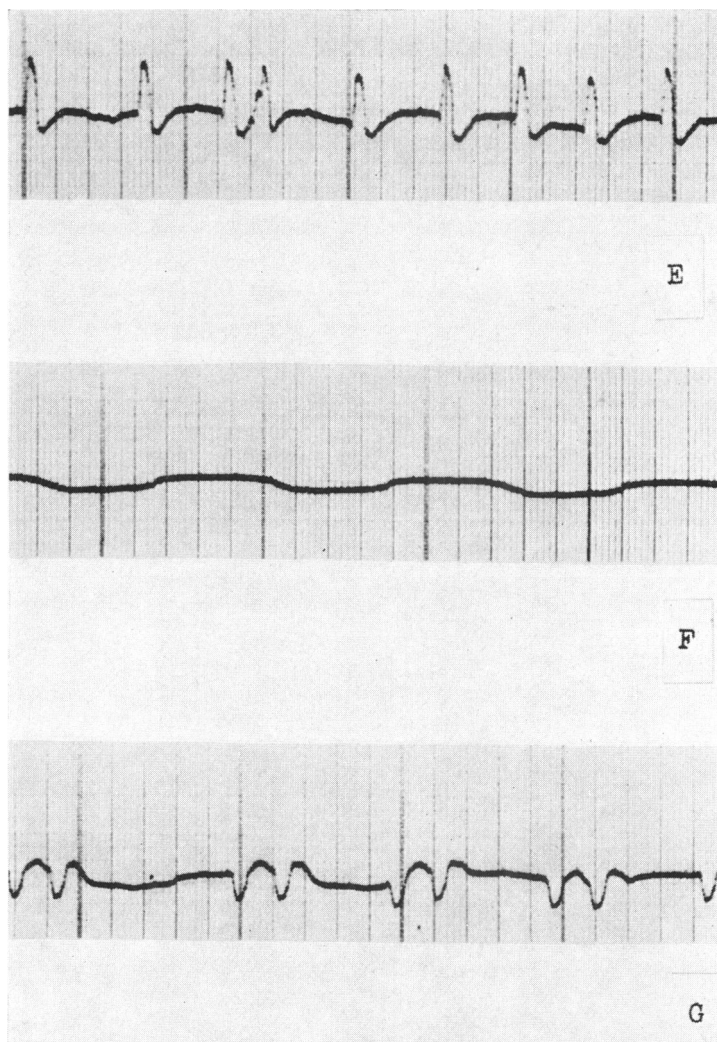


FIG. 3 (*continued*).—Defibrillation with Type I apparatus (rabbit). (E) Same animal as (D) after 5 min. cardiac massage (bundle-branch block); (F) Immediately following 100-volt defibrillating shock for 0.5 sec. (virtual asystole); (G) Same animal as (F) after 5 min. cardiac massage (? Ventricular complexes and bundle-branch block).

tions were made in a quiet laboratory, and even under these ideal circumstances, the stimulus duration had a wide range, and with several operators was sometimes dangerously long. Under the “stress” of hurried mental arithmetic, the mean stimulus duration and variability were further increased in most cases; it is probable that in the stress of a true emergency, the range of timing would be even wider.

The stimulus duration with Model II depends partly on the characteristics of the fuse (Belling-Lee type 0.1 ampere cartridge), but much more on the resistance across the electrodes. If the fuse is carefully inserted in its holder, the rate of fusing can be controlled quite closely at a given current strength (the manufacturers claim to within 5%). However, the rate of fusing is also a logarithmic function of the applied current, and this can vary quite widely according to the size of heart and

efficiency of electrode application. Values obtained for some common fuses, using a high-speed cathode-ray oscilloscope and direct current are shown in Table II. The Belling-Lee type 0.1 ampere fuse will withstand a current of 2 amperes at mains voltage for as long as 10 seconds.

TABLE II
TIME (SEC.) TO FUSING OF SELECTED FUSES. VOLTAGE 220 D.C.

| Fuse type and rating | Current (amperes) | | | | | | | |
|---------------------------------|-------------------|----------|-----------|-----------|-----------|-----------|-------|-------|
| | 1 | 1.4 | 1.7 | 2.2 | 2.8 | 3.7 | 5 | 10 |
| <i>Glass fuses</i> | | | | | | | | |
| <i>B.L. type O (standard)</i> | | | | | | | | |
| 1 amp. | ∞ | ∞ | >20 | 0.33-0.38 | 0.15-0.16 | 0.03 | 0 | 0 |
| $\frac{1}{2}$ amp. | 9 | 0.17 | 0.08 | 0 | 0 | 0 | 0 | 0 |
| $\frac{1}{4}$ amp. | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Elpico type O (standard)</i> | | | | | | | | |
| 1 amp. | ∞ | >20 | — | 0.30-2.0 | 0.14-0.18 | 0.07-0.08 | 0 | 0 |
| <i>B.L. type OO (miniature)</i> | | | | | | | | |
| 1 amp. | ∞ | ∞ | >20 | 0.09 | 0.04 | 0.02 | 0 | 0 |
| $\frac{1}{2}$ amp. | >20 | 0.03 | 0.02-0.04 | — | — | 0.005 | 0 | 0 |
| $\frac{1}{4}$ amp. | 0.05 | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Ceramic (H.R.C.) fuses</i> | | | | | | | | |
| <i>B.L. type O (standard)</i> | | | | | | | | |
| 1 amp. | ∞ | ∞ | ∞ | >20 | 0.06 | 0.01 | 0 | 0 |
| <i>E.E. type O (standard)</i> | | | | | | | | |
| 1 amp. | ∞ | ∞ | ∞ | >20 | 0.15 | 0.07 | 0.01 | 0.008 |
| $\frac{1}{2}$ amp. | ∞ | 1.7 | 0.09 | 0.02 | 0.01 | 0.008 | 0.006 | 0 |
| $\frac{1}{4}$ amp. | 0.02 | 0.009 | 0.007 | 0.005 | 0 | 0 | 0 | 0 |
| <i>E.E. type OO (miniature)</i> | | | | | | | | |
| 2 amp. | ∞ | ∞ | ∞ | ∞ | ∞ | >20 sec. | 0.3 | 0.006 |
| 1 amp. | ∞ | ∞ | ∞ | 10.1 | 0.01 | 0.007 | 0.006 | 0 |
| $\frac{1}{2}$ amp. | >20 | 0.02 | 0.009 | 0.006 | 0.005 | 0 | 0 | 0 |
| $\frac{1}{4}$ amp. | 0.017 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Non-standard rating fuse</i> | | | | | | | | |
| 1 amp. | ∞ | ∞ | ∞ | ∞ | ∞ | 0.15 | 0.10 | 0.01 |

Notes: (1) Belling-Lee (BL) standard glass (type O) is normally used in the University College defibrillator. The manufacturers specify that it will fuse within 10 sec. at twice the rated current.

(2) English Electric (E.E.) claim that the time to fusing of their cartridge fuses is reproducible to within 5%.

(3) Providing that current loadings are expressed as root mean square values, the time to fusing will be very similar at 230 volts a.c.

The timing of the stimulus is quite critical if thermal coagulation is to be avoided, and while it may be possible to train an operator to depress a switch for short periods, it would seem simpler and safer to make the primary system a resistance-capacitance timing circuit as in some forms of Model III and in the Porton defibrillator. Several pre-selected durations of stimulus are also preferable to a continuously variable time adjustment for emergency use.

Electrode Design. Probably because it is readily available in the operating theatre, most writers have advocated dipping the electrodes in saline to improve their conductivity (Leeds, 1953) and in some cases the lint or gauze covering of the spoons has also been impregnated with salt (Lucas, 1959) so that the solution introduced into the heart is hypertonic saline. On theoretical grounds, there is little advantage in adding to the pericardium fluid of greater electrical conductivity than the blood; this point is reached with approximately isotonic solutions. Further, there is little difference in conductivity between saline and more physiological fluids such as mammalian Ringer.

Practical Experience of Different Systems

Model I. In the rabbit, defibrillation was uniformly successful with very short shocks (tapping rather than pressing the switch). At 50 volts, there was usually an immediate return to normal

rhythm and no signs of burning when the animals were finally killed. Occasionally two shocks were needed to stop fibrillation. At 100 volts, a short shock gave rise to A-V block, but with some minutes of cardiac massage a normal rhythm could often be restored (Fig. 3). A longer shock (about 0.5 sec.) at 100 volts gave complete asystole, and prolonged massage was needed to restore a regular rhythm: this was poorly maintained, and the animal subsequently died. At post-mortem, there were two longitudinal areas of hard, coagulated tissue in the myocardium, one extending up to the coronary vessels, which contained large bubbles of gas (Fig. 4). Histological examination confirmed extensive coagulation and disorganization of the myocardium (Fig. 5). At 200 volts, the instantaneous current must have exceeded 15 amperes r.m.s., since the 5-ampere transformer fuse blew with even the shortest shocks.

Model II. Defibrillation always resulted, although typically an A-V block was produced immediately, and massage was needed to restore a normal rhythm. In some animals, block persisted, and in these recovery with spontaneous respiration did not occur. At subsequent post-mortem, some burning was usually found, ranging from slight epicardial damage to deeper coagulation of the myocardium.

Controlled Current Devices (Model III and Porton Defibrillator). In none of the rabbits tested was it necessary to use a current greater than 2 amperes root mean square (r.m.s.) to produce defibrillation. Sometimes a pulse as short as 1/30th second sufficed to restore a normal rhythm, and it was never necessary to apply the current for longer than 1/10th second. Under these conditions, no burning of the heart was observed. The maximum current needed (2 amp.) agrees well with the finding (above) that 50 volts is adequate to defibrillate the rabbit. Somewhat longer and

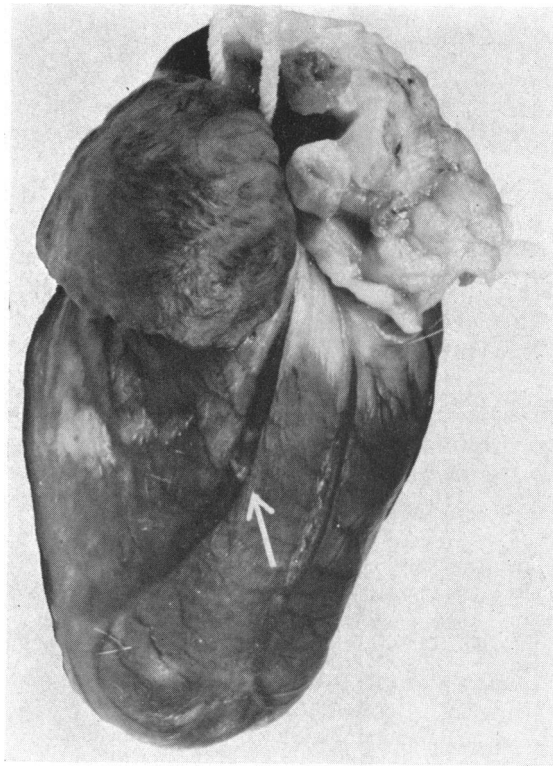


FIG. 4.—Rabbit heart following defibrillation with 100-volt shock for 0.5 sec. using Model I defibrillator. There is a longitudinal burn (arrowed) of the interventricular coronary vessels, which are filled with bubbles.

stronger pulses might be needed in man, but the upper limit set for the Porton apparatus (5 amperes r.m.s. for 0.2 sec.) would seem a safe and adequate maximum. The commercial controlled current device is stated to have a similar maximum current output.

Electrode Design. Spoon shaped electrodes covered either with lint or with four layers of gauze proved equally satisfactory. When the electrodes were dipped in normal or hypertonic saline before application, the cardiogram invariably showed abnormalities, usually with slurring of the S-T segment or T wave inversion; after 5-6 minutes arrhythmias sometimes appeared. Such changes could be reversed by repeated washing with normal or hypertonic mammalian Ringer (Fig. 6). Cardiographic abnormalities of similar type could be induced by instilling saline solution into the pericardium. Mammalian Ringer never caused any adverse effect on the electrocardiogram.

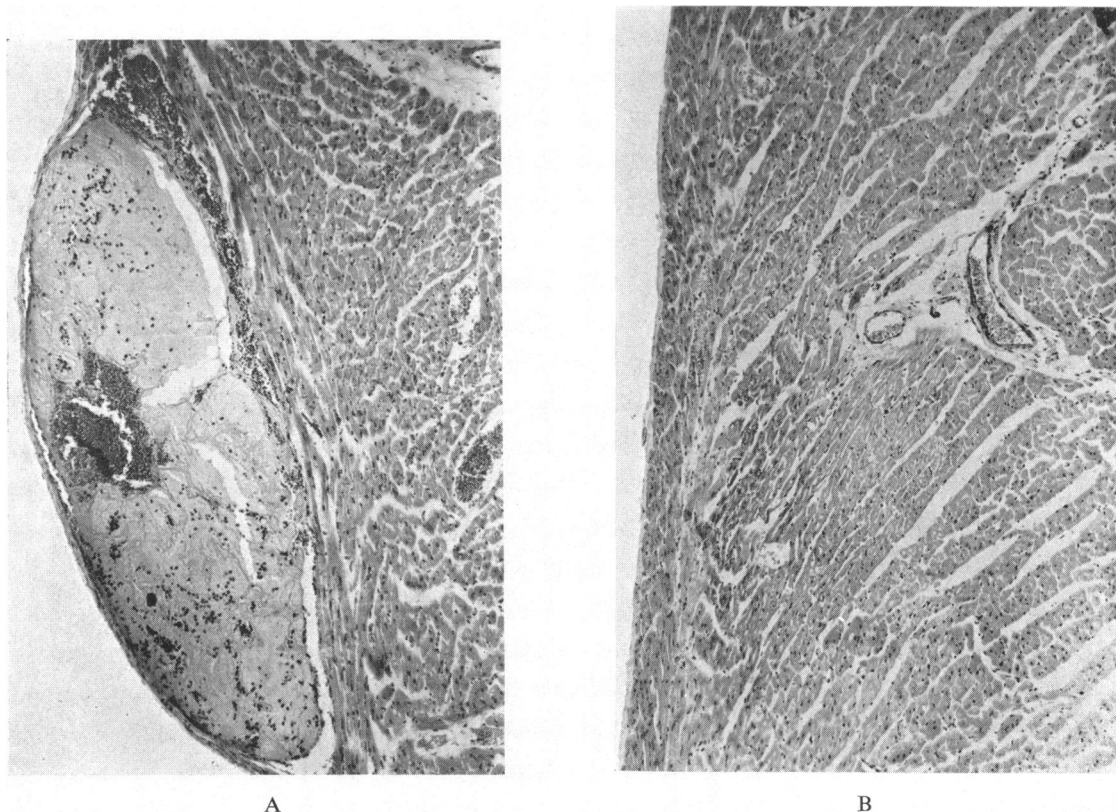


FIG. 5.—Histological changes after defibrillation of rabbit heart. (A) Destruction and heat coagulation of blood in large coronary vessel. After exposure to 100-volt shock for 0.5 sec. (H & E $\times 60$). (B) Some oedema of epicardium, and coagulative necrosis of myocardium. After exposure to 100-volt shock for 0.5 sec. (H & E $\times 60$).

DISCUSSION

The present experiments suggest that with defibrillators lacking precise time and current control, the *two main dangers* are undue local heating of the cardiac muscle, and the production of resistant asystole. In the rabbit, 100 volts for 0.5 sec. produced a serious burn.

Local Heating. The rabbit heart has a lower electrical resistance than the human heart, and burning will therefore tend to occur at a lower voltage; the electrodes are also smaller, giving a relative increase in the local current density. On the other hand, larger voltages are commonly used in man, and on theoretical grounds it seems likely that application of current for a similar time may have equally deleterious effects on human cardiac muscle.

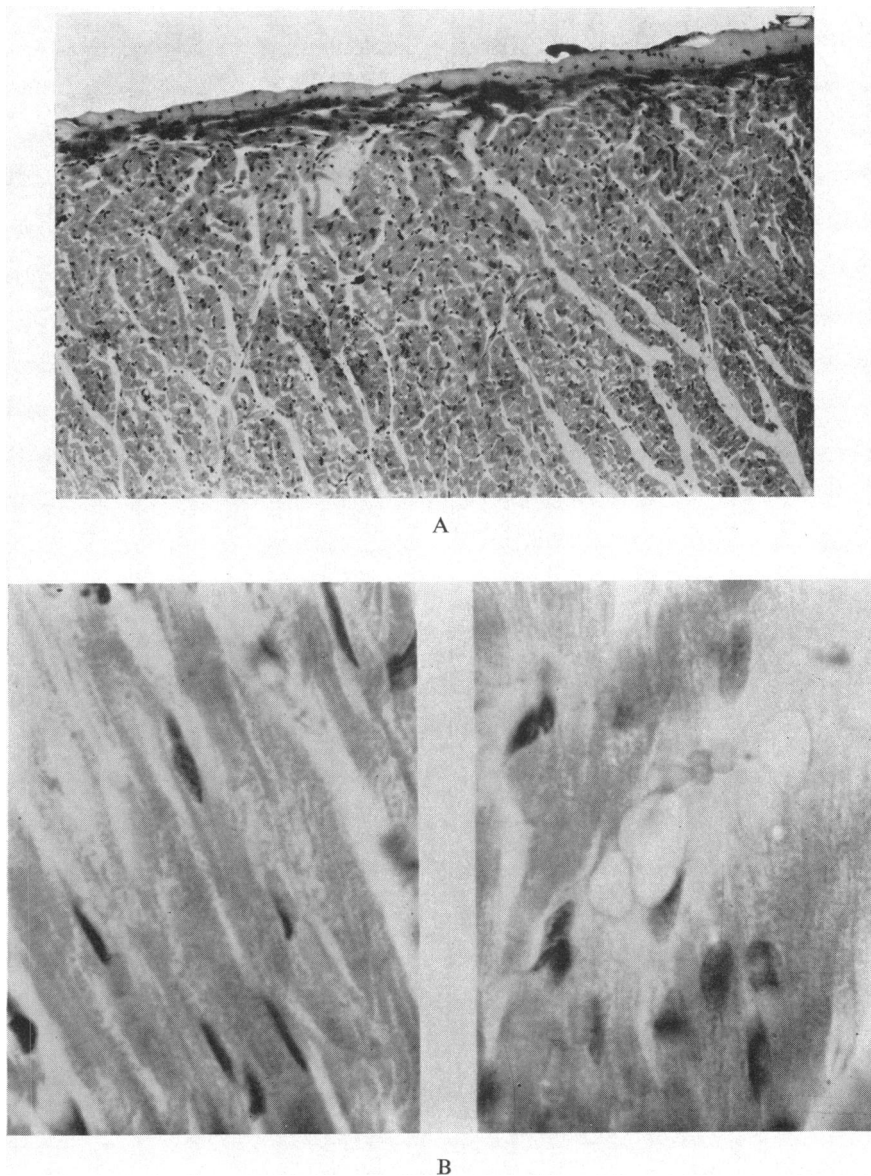


FIG. 6.—Histological changes after defibrillation of rabbit heart. (A) More extensive oedema of epicardium and myocardial damage. After exposure to 200 volt shock for 1 sec. (B) High-power view of myocardium in Fig. 6 (A). Comparison of normal (*left*) and burnt (*right*) tissue. Both H & E. $\times 60$.

Assuming electrical contact is adequate to prevent arc formation, then the average rate of heating of the cardiac mass can be calculated by Joule's law. Assuming power dissipation to be at the rate of 2000 watts/sec. as is possible in the simple mains voltage models, the mass of the blood-filled heart to be 600 g., and the specific heat of both blood and cardiac muscle to be unity, then the general temperature of the cardiac mass will rise by $0.75^{\circ}\text{C./sec.}$ However, local heating in the vicinity of the electrodes will be 30–70 times more rapid, because of the smaller cross-section of the current path ($<20\text{ cm.}^2$ at the electrodes, compared with 70 cm.^2 in the heart proper) and the greater resistance of cardiac muscle as compared with

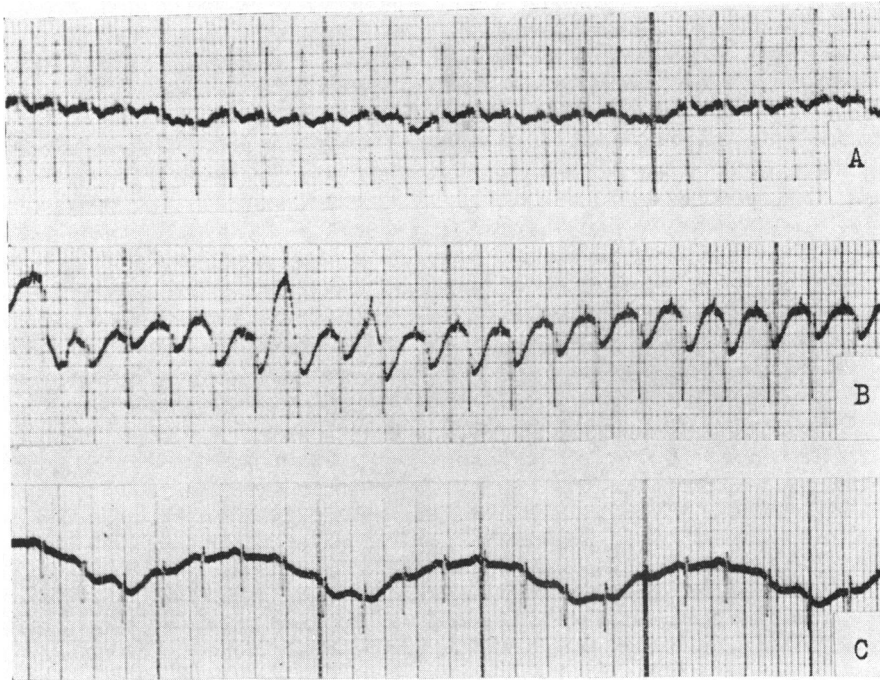


FIG. 7.—Effect of saline-filled electrodes on electrical conduction in rabbit heart. (A) Control observation (open pericardium). Normal sinus rhythm; (B) Electrodes in contact with heart for 2 minutes. Sinus rhythm, but increased P-R interval and depression of S-T segment; (C) After removal of electrodes and repeated rinsing with mammalian Ringer fluid. Sinus rhythm, S-T segment again has normal appearance. P-R interval still longer than in (A).

blood. Thus, at the point of application of the electrodes, temperatures can rise at a rate of 50°C./sec. If the initial temperature of the part is 30°C. , and 40°C. be accepted as the safe upper limit of heating it will be dangerous to apply the mains voltage for more than 0.2 seconds.

It is significant that from practical experience McMillan (1955) considers that “0.5 sec. is long enough for electrical burns to be produced”; he recommends 0.2 sec. as the stimulus duration for the St. Thomas’s defibrillator. The greatest risk of burning is at the points where the electrodes are applied; this danger can be decreased by increasing the surface area of the electrodes and by dipping them in a conducting fluid (Leeds, 1953). However, despite these precautions, the figures for the push button switch (Table I) suggest that many operators would produce burning particularly in emergency use of the apparatus. The fuse-limited device will be particularly dangerous to the patient if contact is poor, as if the current is less than two amperes it may flow for ten seconds or longer.

The clinical prognosis of a myocardial burn is probably similar to that of an infarct in a comparably anoxic heart. Anaesthetists have known patients to recover despite marked burning (Lucas, personal communication), but the presence of injured tissue must worsen the chances of recovery, and the tendency to arrhythmia may actually be increased by the injury, particularly if the coronary vessels are involved.

Can stimulus duration be reduced further? Values of 0.1–1.0 sec. have in the past been recommended largely on an empirical basis. Such times bear little relation to the accepted cardiac chronaxie of 3–4 m.sec. (Lovatt Evans, 1952). It may be that a large part of the applied current traverses the blood within the heart rather than the cardiac muscle, and that in many areas of the

wall the current density fails to reach the rheobasic value. If this is the case, the parts of the muscle wall immediately depolarized must be maintained in an unexcitable state while the impulse is conducted to the remainder of the ventricular tissue. At the normal conduction rate of 50 cm./sec. (Lovatt Evans, 1952), and with a heart of normal dimensions, this is unlikely to require more than 0.1 sec. Even with the largest heart, the maximum requirement should not exceed 0.2 sec., and any form of apparatus providing the possibility of a longer current application is not only potentially dangerous, but also unnecessary.

Production of Asystole. The importance of cardiac asystole is more controversial. Some clinicians consider asystole as the normal response to a defibrillating shock (Lucas, personal communication), but the present experiments would seem to suggest that in the rabbit it is more likely to occur when the current strength is excessive. It is possible that the rabbits were in better condition than the typical unconscious patient, although fibrillation had usually been maintained for some minutes before the defibrillator was tested. Further observations are needed on patients under emergency conditions, but if it can also be substantiated in man that an unnecessarily large or maintained current increases the chance of atrio-ventricular block (perhaps by direct injury of the conducting system), this will be a further powerful argument in favour of careful control of current and stimulus duration.

Selection of Method of Defibrillation

Optimum Conditions. Choice of stimulus strength and duration is governed by two opposing factors. An excessive shock may cause burning or asystole, while an inadequate shock fails to defibrillate with consequent further deterioration of cardiac and general condition. In general it would seem better to increase the stimulus duration rather than the current, since heating is directly proportional to time, but is proportional to the square of applied current. In the rabbit, 100 volts (\approx 8 amp.) for 0.2 sec. is the upper limit of safety, and in the larger human heart this is 250 volts (\approx 12 amp.) for 0.2 sec. (McMillan, 1955). For an averaged-sized human heart 1 ampere for 0.1 sec. is probably the optimum initial shock. If this does not produce defibrillation, the duration should be increased to 0.2 sec., and should this still be ineffective, the amperage should be increased in stages to 5 amperes. With a large heart, an initial duration of 0.2 sec. would be selected and with a child's heart an initial value of 0.05 sec. would be more suitable.

Choice of Defibrillator. Some clinicians have argued that there is a case for a "simple" defibrillator, such as Model II. Advantages that have been claimed are simplicity, cheapness, and elimination of a need for regular testing. Simplicity of operation (but not necessarily of design) is desirable in emergency equipment; however, such could be obtained with "controlled" apparatus by pre-setting the controls at a safe maximum (for instance, 5 amp. 0.2 sec. pulse). The cost of apparatus such as the Porton defibrillator is inevitably higher than a simple fuse box system, but is not excessive as it can be assembled quite quickly from standard components by the average hospital or laboratory workshop. The expenditure of a few additional pounds (the commercial price of Model II is £6 10s. 0d.) is a small price to pay for the additional safeguards obtained. Elimination of a need for testing is also probably an illusory advantage, as even with the simplest apparatus damage to leads and corrosion of switches can occur with time. Further, regular testing ensures that the staff are familiar with the equipment.

The present work indicates that an apparatus in which there is control of both stimulus duration and strength is required if cardiac damage is to be consistently avoided. Model III meets most of the requirements when fitted with an electronic time switch. However, the Porton defibrillator incorporates certain additional safeguards, including selection of current prior to use, and a secondary timing system in the remote event of failure of the electronic mechanism.

Electrode Composition. The use of pure saline as a bathing fluid for the heart has been deprecated since the classical experiments of Ringer (1883), and the present observations show that saline impregnation of the electrodes has an adverse effect on subsequent electrical conduction in the rabbit heart. Brine may be slightly less harmful in man because of the larger initial volume of

pericardial fluid, but here, too, it no doubt contributes to the "current of injury" seen after defibrillation. There is nothing to commend saline except its availability in the operating theatre. At a comparable dilution, mammalian Ringer has a similar electrical conductivity, and it would seem a simple matter to keep a pint bottle of sterile mammalian Ringer fluid in every defibrillator set.

SUMMARY

Three commercial defibrillators are described and also a new defibrillating apparatus developed at Porton.

On theoretical grounds all three commercial models are hazardous because there is no second line of defence against switch or fuse failure, and all can supply too large a current for too long a time. These defects are overcome in the Porton defibrillator.

Experimental evaluation has shown that all types of apparatus could stop electrically induced ventricular fibrillation in the rabbit. However, excessive strength or duration of stimulus with the commercial models produced severe burning of the myocardium and an atrioventricular block or asystole rather than a normal sinus rhythm.

The introduction of saline into the pericardium caused severe abnormalities of electrical conduction, which were reversed by application of mammalian Ringer solution. The latter solution should always be used for impregnating cardiac electrodes.

The Porton defibrillator is slightly more costly than some forms of defibrillator, but the added price is small compared with the extra safeguards that are obtained.

I am indebted to Dr. B. G. B. Lucas, consultant anaesthetist, for his stimulating discussion of this manuscript. Crown copyright of the illustrations is reserved, and these are reproduced with the permission of the Controller, H.M.S.O.

REFERENCES

- Beck, C. S., Weckesser, E. C., and Barry, F. M. (1956). *J. Amer. med. Ass.*, **161**, 434.
 Johnston, T. B., and Whillis, J. (1945). *Gray's Anatomy*. 28th ed., Longmans, Green & Co., London.
 Kelly, K. M. (1959). *Lancet*, **2**, 619.
 Leeds, S. E. (1953). *J. Amer. med. Ass.*, **152**, 1409-1413.
 Lovatt Evans, C. (1952). *Principles of Human Physiology*. J. & A. Churchill Ltd., London.
 Lucas, B. G. B. (1959). *Lancet*, **2**, 163.
 McMillan, I. K. R. (1955). *Brit. med. Bull.*, **11**, 229-232.
 Perry, B. J., and Trotman, R. E. (1958). *Electronic Engineering*, **30**, 24.
 Rajewsky, B., and Schwan, H. (1944). *Z. ges. exp. Med.*, **113**, 553.
 Ringer, S. (1883). *J. Physiol.*, **4**, 29.
 Walton, R. S. (1960). *Brit. med. J.*, **1**, 155.
 Wyatt, D. G. (1959). *Lancet*, **2**, 619.